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Coupling simulation of seepage and temperature characteristic of Single-well circulation geothermal collection system

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ABSTRACT

Single-well cycling geothermal collection technology collects shallow thermal energy through the circulating flow of groundwater in a closed single well, which does not consume or pollute groundwater. The technology has been promoted and applied for more than 20 years, and the application building area exceeds 20 million square meters. In order to further study the operation characteristics of this technology, the influence of system operation on groundwater seepage and temperature field is explored by combining theoretical research and numerical simulation. Firstly, a mathematical model of single-well cycling geothermal collection technology is established, and the theoretical solution of groundwater drawdown is derived, which is applied in practical engineering. Secondly, a three-dimensional water-thermal coupling numerical model is established to simulate the effects of changing pumping flow rate, aquifer permeability coefficient and operation mode on the distribution of seepage and temperature field. The results show that when the pumping flow increases by 50%, the waterhead at the injection section increases by 5m, while the pumping temperature changes by only 0.3 ºC. The permeability coefficient of aquifer affects the flow of circulating water underground, the injection water is blocked to flow to pumping zone when the permeability of aquifer in clapboard section is poor, which significantly reduces the fluctuation of pumping temperature, and a stable heat transfer temperature difference will be maintained. While the long-term single-season operation mode (simple heating/cooling) is prone to heat/cold accumulation, resulting in a decrease in the heat transfer efficiency of the system in this season, which further indicating that intermittent operation mode with both of heating and cooling as a complete cycle should be adopted to maintain the high efficiency and sustainable operation of the system.

1. INTRODUCTION

The key for the thermal energy sector to help decarbonize lies in the use of new energy technologies to adjust the proportion of traditional heating and cooling energy consumption in building energy consumption, so as to achieve energy saving and reduce the amount of carbon dioxide emitted by the utilization and consumption of fossil fuels. Under the background of the dual carbon target, the adjustment of energy structure and the clean energy heating policy further promote the development and utilization of geothermal energy in the forefront of energy (Zhao and You, 2020).

Shallow low-geothermal refers to soil and water at a certain depth below the surface (200 m), which is mostly a constant temperature zone and remains between 10 ℃ and 20 ℃ (Chua and Chou, 2010). Taking advantage of the stable temperature of groundwater, it is used as a energy source for buildings in winter heating, summer cooling and domestic water, and the initial investment of construction and operation is lower than that of traditional methods (Nam and Ooka, 2012). However, due to the small energy density of shallow low-temperature geothermal energy, it is difficult to develop large areas. The single-well circulation geothermal collection system (SWC) was invented and developed by Beijing Ever Source Science & Technology Development Co., Ltd, and Fig. 1 shows how the system works (Tu and Wu, 2019). Compared with other groundwater source heat pumps, the initial investment in single-well circulation collector system is reduced by 2/3-3/4 (Xu and Ladislaus, 2003), at the same time, the pressure difference between the recharge zone and the pumping zone drives the injection water through the injection well into the aquifer, improves the recharge efficiency, avoids the problem of recharge difficulties, and the system achieves high efficiency without water-consuming for heating and cooling. the application of SWC system will be beneficial for reduction in greenhouse gas emission, environmental pollution and global warming effects (Rybach,2015).

The popularization and application of single well technology also promote the basic theory, model development, structure configuration and system optimization research of single well circulation heat collection system to grasp and improve the operating efficiency of the system (Samjil, 2022, Deng and Spilter, 2006; Paul and Simon, 2020). The performance of geothermal capture systems is evaluated based on various performance criteria, such as the critical heat extraction rate, sustainability, and economic efficiency (Zeng and Zhou, 2017). These performance indicators are affected by the relevant attribute parameters of underground, building and system design, including geothermal gradients, hydrological and thermal geological conditions (Li and Yuan, 2011). From the perspective of underground heat exchangers, the heat exchange efficiency of a single well recycling geothermal energy collection system is directly controlled by the temperature difference between pumping and surface environment. In contrast, the sustainability of the system is determined by the comprehensive effect of the seepage field and temperature field of the aquifer in long-term operation.

In order to study seepage and thermal plume, plenty of researchers on single well system have been carried out. Based on the Hantush-Jocab formula of groundwater flow, the analytical solution of groundwater drawdown in the same pumping and injection wells was obtained by the superposition method. Subsequently, Ni et al. (2011) established the analytical model of single-well circulating heat collection system in confined aquifer, and obtained the expression of effective hydraulic radius of system operation. The basic theory of water-saturated zone research is various groundwater dynamics equations developed at the center of the Navier-Stokes equation. Since then, groundwater seepage and heat transfer in single-well circulating energy recovery systems were studied by analytical methods (Li and Diao, 2006). Song et al. (2019) conducted a physical simulation test study on the structural characteristics of the single-well circulation system, and discussed the influence of the distance between pumping and returning water, the initial aquifer temperature, the pumping flow rate and the variation of the load bearing capacity of the thermal well on the heat transfer performance of the single-well system. Zhou et al. (2013) established a numerical simulation model through the established test system, and concluded that in aquifers with high porosity and hydraulic conductivity, the direction and velocity of groundwater seepage directly affect the variation of underground temperature field. With the deepening of research, the influence of long-term pumping and injection process on land subsidence deformation and water environment change is gradually considered, and the corresponding more complex three-dimensional thermal-hydrological-mechanical coupling (THM) combined model is gradually proposed to study the energy production analysis of single well cyclic heat exchange system with multi-flow field coupling (Li and Luo, 2022; Wu and Sun, 2019). Cui et al. (2018) proposed a mathematical model of ground deformation to consider the influence of particle deposition on ground deformation during pumping and irrigation; Based on linear thermoelastic theory, Kong et al. (2005) established a THM coupling mathematical model including seepage equation, constitutive equation and energy equation.

The purpose of this study is to develop a unsteady mathematical model to deal with groundwater seepage and heat transfer caused by a single well system with both pumping and pumping functions. In addition, the model is analyzed to obtain the theoretical solution of groundwater seepage, and the model is applied to a case study to describe the influence of the operation of a single well system on the seepage field and temperature field of the aquifer.

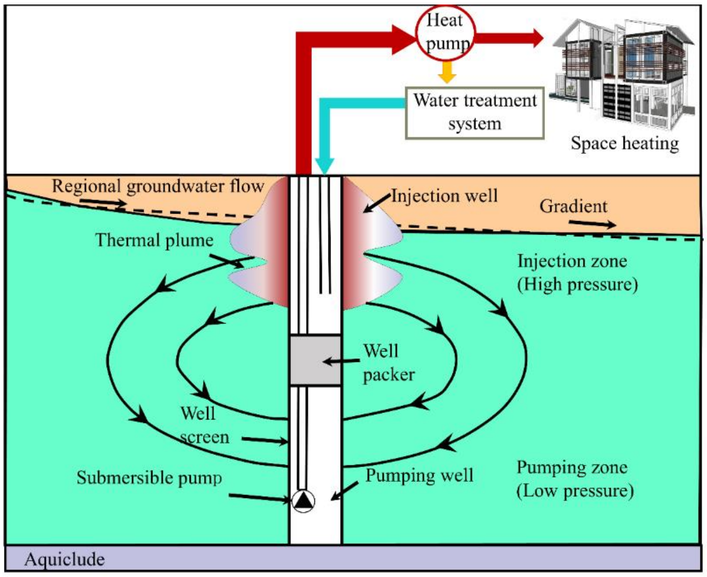


Fig. 1 A schematic diagram of a single well circulation groundwater heat hump system (Tu and Wu, 2019)

2. MODE AND CHARACTERISTICS OF SWC

Single-well circulation geothermal collection system is a new generation of shallow geothermal energy collection technology invented by Beijing Ever Source Science & Technology Development Co., Ltd, among which hydrogeological conditions are one of the main controlling factors affecting the operation efficiency. Combined with the recharge predicament and the hydrogeological conditions of the engineering site, three modes are proposed with the single well circulating heat collection technology as the core.

2.1 SWC without heat transfer backfilled particles

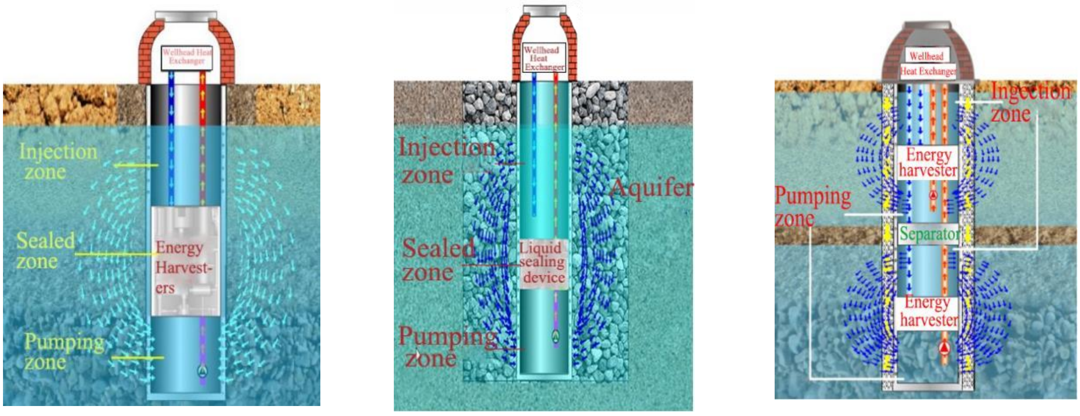
SWC without heat transfer backfilled particles is suitable for stratum with preferable permeability, such as coarser porous medium size of the quaternary loose layer, developed bedrock fractures, umbrella source of alluvial-diluvial fan and intermediate section, which means that there is no need for backfill particles to assist groundwater flow and diffusion. The thermal well is divided into the negative pressure suction chamber, middle sealing chamber and upper positive pressure injection zone (Fig. 2). During the operation, the groundwater is pumped to the ground heat exchanger through the suction chamber, after the heat exchange with the circulating working medium of the heat pump unit, the groundwater is injected to the original aquifer through injection chamber to form the groundwater recycling. The main driving force of groundwater seepage comes from the pressure difference between the injection chamber and suction chamber, as well as the aquifer head difference formed around the well during the system operation, so that the injection efficiency is realized 100%.

2.2 SWC with heat transfer backfilled particles

SWC with heat transfer backfilled particles (Fig. 2b) is applied to stratum with poor permeability, such as fine porous medium size of the quaternary loose layer, undeveloped bedrock fractures or the former source of alluvial-diluvial fan. This mode is mainly used to deal with the development bottleneck constraints of hydrothermal geothermal development in the strata with weak permeability and small unit water inflow. Based on SWC without backfilled particles, the heat transfer backfill particles with large porosity are filled between the well pipe and the well wall. The local aquifer permeability is improved to ensure the building load and the pumping water required for the continuous and stable operation of the system, and the pumping water pressure is effectively reduced. It is worth noting that this model is accompanied by a relatively rapid thermal translocation phenomenon, and part of the underground tail water after heat transfer enters the backfill area and then directly transfers to the pumping area after convective heat transfer.

2.3 SWC stratified heat collection

Multi-aquifer single-well circulating stratified heat harvesting technology was developed for the thick quaternary loose layer with multiple aquifers (Fig. 2c). Multiple single well circulation modules are superimposed, and the thermal well is divided into multiple pumping and injecting subsystems by the sealing device. It realizes pumping and injecting water from the same aquifer at different depths in the same radial well, which can avoid groundwater cross-layer pollution, it solves the challenge of the traditional doublet well can only mix the water and cannot recharge in the same layer.



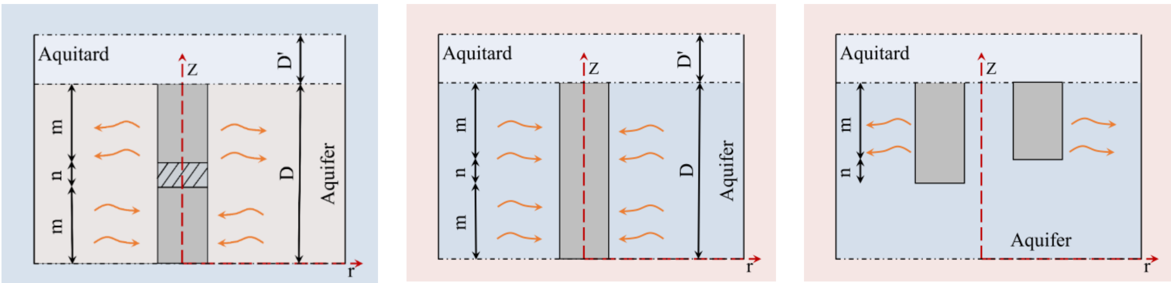
a) Without backfilled particles b) With backfilled particles c) through multiple aquifers

Fig. 2 Three modes of single-well circulation heat transfer

3 GROUNDWATER SEEPAGE EQUATION SOLUTION OF SWC SYSTEM

3.1 Groundwater seepage equation

The mathematical model of SWC is shown in Fig. 3, and the thermal well is axisymmetric. The intersection point between the axis of the well and the floor of confined aquifer is set as the origin of coordinates. Confined aquifer horizontal to the right is the positive direction of *r* coordinate; the thickness of confined aquifer is *D*, which floor is impermeable, and the thickness of the weakly permeable roof is *D'* refers to the thickness of roof aquitard. the sealed zone is presented as *n*, while the injection and pumping zone are assumed as same height *m*.



a) SWC b) Complete well c) Non-complete wells

Fig.3 Mathematical model of single well circulation system

The appropriate assumptions and constraints are proposed:

1) 1) Confined aquifer is homogeneous and anisotropic, with equal thickness and infinite horizontal extension;

2) Leakage recharge through aquitard existing in the aquifer upper, and the recharge intensity is proportional to the variation of the level of confined aquifer. The aquifer floor has water resisting property.

3) The seepage velocity of groundwater is evenly distributed along the wall of pumping zone and injection zone while pumping with constant flow rate.

4) The flow of groundwater in the confined aquifer follows Darcy's law. The storage and release of groundwater from the aquifer are completed in an instant.

The mathematical model includes the seepage differential equation and the definite conditions of the confined aquifer. Base on the groundwater dynamics theory and the assumption conditions of the single-well circulation system, the control equation considering the groundwater flow of the anisotropic confined aquifer under the overflow conditions is shown as Equation 1.

$$\begin{cases} K_r(\frac{\partial^2 s}{\partial r^2}+\frac{1}{r}\frac{\partial s}{\partial r})+K_z\frac{\partial^2 s}{\partial z^2}-\frac{K's}{K'D}=\mu s\frac{\partial s}{\partial t} \\ s(r,z,t)\big|_{t=0}=0, \quad s(r,z,t)\big|_{t=\infty}=0 \\ \frac{\partial}{\partial z}s(r,z,t)\big|_{t=0}=0, \frac{\partial}{\partial z}s(r,z,t)\big|_{t=D}=0 \\ \lim_{\gamma\to\gamma_v} r\frac{\partial}{\partial r}s(r,z,t)=\begin{cases} \frac{-Q}{2\pi K_r m} & (0<z<m) \\ 0 & (0<z<m+n) \\ \frac{Q}{2\pi K_r m} & (m+n<z<D) \end{cases} \end{cases}$$

(1)

Where *s* is groundwater drawdown [m], *r* and *z* represent the radial and vertical coordinates [m], *D* and *D'* refers to the depth of aquitard and confined aquifer [m], *m* denote the lengths of pumping and injecting well, respectively [m]. *n* is the depths of the sealed zone [m], *Kr*, *Kz* and *K* denote the horizontal, vertical and aquitard hydraulic conductivity, respectively [m/s], the pumping and injection rate *Q* are the same and constant [m^3/s], μ_s refers to the elastic storativity of an aquifer.

3.2 Solution of the model

For the fixed flow single well circulation system of the same homogeneous aquifer, the parameters K_r, K_z and *Q* in the mathematical model are regarded as constants in time and space, and the thermal well of the SWC system can be regarded as a pumped complete well with a depth of 2*m*+*n* and two recharge incomplete wells with a depth of *m*+*n* and *m*, respectively (Fig. 3b, 3c), and the drawdown of the SWC system is considered to the superposition of the corresponding drawdown function s of the pumping well and two injection well, as shown in Equation 2.

$$s(r,z,t)=s_1(r,z,t)+s_2(r,z,t)+s_3(r.z.t)$$

(2)

The theoretical solutions of drawdown for pumping complete well and incomplete wells in single well circulation system are obtained:

$$s_1(r,z,t)=\frac{Q}{4\pi m K_r}W(\mu_r,\frac{r}{B_r})$$

(3)

$$s_2(r,z,t)=-\frac{Q}{4\pi m K_r}\left\{W(\mu_r,\frac{r}{B_r})+\frac{2D}{\pi m}\sum_{k=1}^{+\infty}\frac{1}{k}\sin(\frac{k\pi(m+n)}{D})\cos(\frac{k\pi z}{D})\times W\left[\mu_r,\sqrt{(\frac{r}{B_r})^2+\frac{K_z}{K_r}(\frac{k\pi r}{D})^2}\right]\right\}$$

(4)

$$s_3(r,z,t)=-\frac{(m+n)Q}{4\pi m D K_r}\left\{W(\mu_r,\frac{r}{B_r})+\frac{2D}{\pi(m+n)}\sum_{k=1}^{+\infty}\frac{1}{k}\sin(\frac{k\pi(m+n)}{D})\cos(\frac{k\pi z}{D})\times W\left[\mu_r,\sqrt{(\frac{r}{B_r})^2+\frac{K_z}{K_r}(\frac{k\pi r}{D})^2}\right]\right\}$$

(5)

Substituting Equations (3)- (5) into Equation (2), the function expression of depth reduction variation of single well circulation system can be obtained after simplification:

$$s(r,z,t)=-\frac{Q}{2\pi^2 m K_r}\times\sum_{k=1}^{+\infty}\frac{1}{k}\cos(\frac{k\pi z}{D})\times\left\{\sin\frac{k\pi z}{D}+\sin(\frac{k\pi(m+n)}{D})\right\}\times W\left[\mu_r,\sqrt{(\frac{r}{B_r})^2+\frac{K_z}{K_r}(\frac{k\pi r}{D})^2}\right] \quad (6)$$

where $\mu_r=\frac{\mu_s r^2}{4tDK_r}, Br=\sqrt{\frac{DD'K_r}{K'}}$, $W(u_r,\frac{r}{B_r})=\int_{u_r}^{+\infty}\frac{1}{y}e^{-y-\frac{r^2}{4B^2y}}dy$ is the fixed flow well function of the first kind leaking system; while t and μr tend to 0, there is $\lim_{\mu_r\to 0}W(\mu_r,\beta)=2K_0(\beta)$, where $K_0(\beta)$ is the second class Bessel function of imaginary argument zero order, which is approximately 0 while $\beta\ge 4$. Therefore, the grondwater drawdown equation of a single-well circulation geothermal collection system in steady status is:

$$s(r,z,t)=\frac{Q}{\pi^2 m K_r}\times\sum_{k=1}^{+\infty}\frac{1}{k}\cos(\frac{k\pi z}{D})\times\left\{\sin\frac{k\pi z}{D}+\sin(\frac{k\pi(m+n)}{D})\right\}\times K_0\left[\mu_r,\sqrt{(\frac{r}{B_r})^2+\frac{K_z}{K_r}(\frac{k\pi r}{D})^2}\right]$$

(7)

where $\beta=\sqrt{\left(\frac{r}{B_r}\right)^2+\frac{K_z}{K_r}\left(\frac{k\pi r}{D}\right)^2}$.

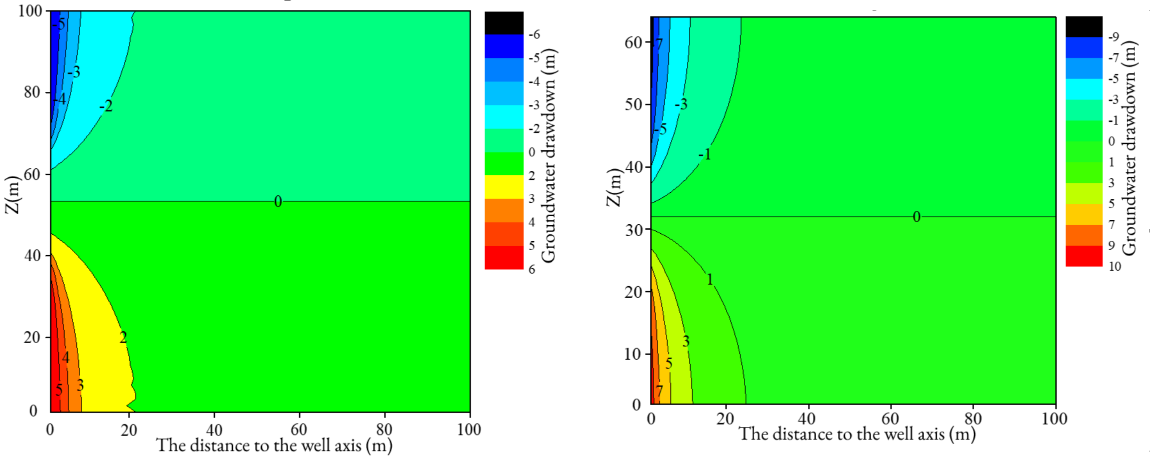
2.3 Aquifer depth influence on drawdown

The analysis if groundwater seepage mathematical model is combined with a SWC engineering project in Haidian District, Beijing, which total heat load is 3459 kW and cooling load 3600 kW. Considering the strong water yield property of research region as well as the water yield reaches to 5000 m³/d, the groundwater drawdown distribution of a SWC system is designed and studied when the aquifer thickness (d) is 100 m and 64 m, respectively. Table 1 shows the parameters of the single-well.

Table 1 The configuration of model parameters

Parameter	Value	Parameter	Value
Aquitard depth	5 m	Pumping zone depth	25 m
K_x	9.1×10^{-4} m/s	Injection zone depth	25 m
K_y	9.1×10^{-4} m/s	Sealed zone	14 m
Aquitard permeability	1.2×10^{-5} m/s	Pumping flow	100 m^3/h
Storage coeffifient	1×10^{-6}	Injection flow	100 m^3/h

It can be seen from the groundwater drawdown distribution of the SWC system that the groundwater pressure is symmetrically distributed due to the particularity structure of the thermal well (Fig. 4). The absolute value of drawdown in the area near the borehole wall is high, and it gradually decreases with the increase of radial distance. Driven by the pressure difference and complementary influence between the pumping and injection zones, the groundwater seepage direction in the upper edge of the pumping area and the lower edge of the backwater area is mainly vertical. The drawdown in the middle aquifer is zero. When the aquifer thickness is thinner, the groundwater drawdown distribution is more significantly affected by the vertical boundary of aquifer roof and floor. The water inflow in the pumping zone contains the dynamic replenishment of the distant aquifer. With the decrease of the aquifer thickness, the absolute value of the groundwater drawdown near the thermal well increases.



a) d=100 m

b) d=64 m

Fig. 4 The distribution of drawdown contours with different aquifer thickness

4 WATER-THERMAL COUPLING SIMULATION OF SWC

The groundwater module and thermal module in the Feflow simulation software were used to analyze the long-term operation characteristics of a SWC system in Beijing. The geological conditions of the engineering site are mainly gravel formations, and 12 sets of single wells are evenly arranged.

4.1 Model construction

The SWC system takes the 6# thermal well as the center and extends 400m around to form the research area. According to hydrogeological and geological conditions, the well group region is vertically generalized into five hydrogeological stratigraphic units. Due to the different mechanism of pumping and injection processes, the influence areas around main working section are further divided (Fig. 6), of which layers I and II are the injection aquifer, as well as V is main pumping aquifer. The model is generalized as heterogeneous anisotropy. Refers to the above conditions, a 3D geometric model with the size of 800 m×800 m×93.94 m was constructed, and the thickness of the sealed zone was set as 2 m. Triangle algorithm was used to generate the finite element mesh, and the mesh around the thermal wells was encrypted and smoothed.

The model operation time is based on the winter heating season (11.15-3.15) and summer cooling season (6.1-9.15) demand in Beijing, and the transition period interval is 137d. The initial conditions include seepage field and temperature field. The initial hydraulic head decreases from 93.94 m at the eastern boundary to 93.60 m at the western boundary according to a linear change law. The horizontal boundary of the study zone has runoff inflow from the Kunming Lake, so it is set as the boundary of fixed water level (Dirichlet condition), and others is set as the boundary of constant flow (Neumam condition). Layers V and VI are thermostatic layers with an initial temperature of 15.50 ℃, and that of other aquifers increases linearly with depth. The temperature of the aquifer at infinity is not affected by operation and is set as the temperature boundary.

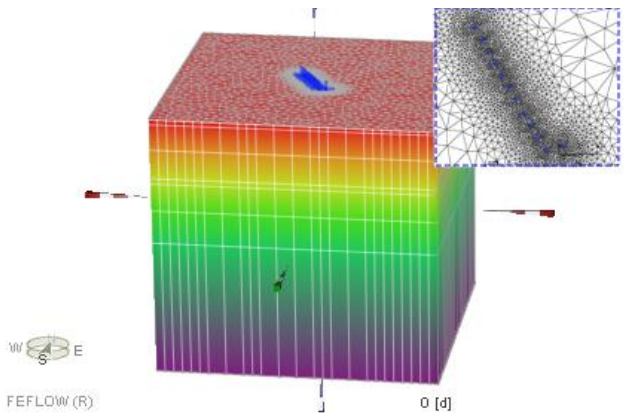


Fig. 5 Three-dimensional grid map of a standing column well site

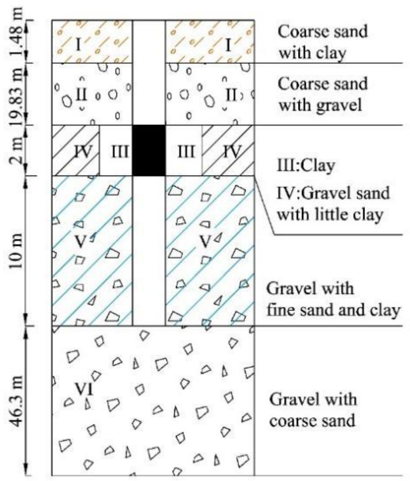
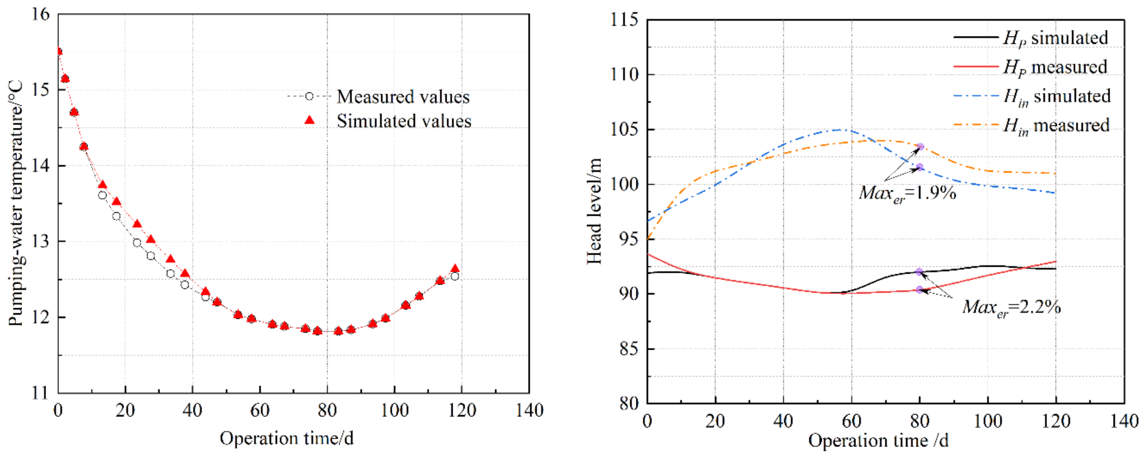


Fig. 6 Lithologic section of a standing column well

4.2 Numerical model verification

It is necessary to make the simulation results credible by using the measured hydraulic head and temperature to fitting the calculation data and adjusting the parameters to calibrate the model. The dynamic variation of pumping water temperature and groundwater hydraulic head during the first heating season were simulated, it can be seen from Fig. 7 that the measured data fit well with calculation curve as whole, among which the average error of the temperature, pumping hydraulic head (*Hp*) and injection hydraulic head (*Hin*) is 0.4%, 0.7% and 1.2%, respectively. The maximum variation of the drawdown depth from the initial value is less than 10%, indicating that the constructed model can be logically used to describe the groundwater flow field during the operation of the SWC system. Combined with the field test and simulation, the corresponding hydraulic parameters and thermal physical parameters of each zone are obtained, as shown in Table 2.



a) b)

Fig. 7 Comparison of the measured and calculated a) Pumping water temperature; b) Hydraulic head during 1st heating period

Table 2 Parameters of groundwater seepage and heat in porous media

Zone	Hydraulic conductivity (m/d)		Porosity	Specific weight	Thermal capacity (MJ/(m³·℃)	Thermal conductivity W/(m·℃)	Dispersion heat transport (m)	
	$K_{xx}=K_{yy}$	Kzz	n	μ	c	λ	D_l	D_t
I	1.00	1.20	0.29	0.01	1.50	1.87	3.0	0.3
II	1.35	1.35	0.30	6×10^{-3}	1.50	1.87	3.0	0.3
III	5.8×10^{-3}	0.3	0.25	5×10^{-4}	1.50	1.87	3.0	0.3
IV	1.8×10^{-4}	1.8×10^{-4}	0.27	5×10^{-4}	1.30	1.35	3.0	0.3

V	1.3	1.3	0.31	1×10^{-4}	1.50	1.87	3.0	0.3
VI	5.01	5.01	0.35	1×10^{-4}	1.50	1.87	3.0	0.3

4.3 Operation strategy of model

The temporal and spatial evolution of seepage field and temperature field of SWC system with different pumping flow rate, operation modes and aquifer permeability coefficient are considering.

(1) Pumping flow rate

Case 1: The average pumping flow in winter is set as 2760 m3/d, and in summer is 1800 m3/d; The temperature of recharge water in heating season and cooling season is 9.6 ℃ and 23.0 ℃, respectively. Case 2: The pumping water will increase by 50%, that is, the average pumping flow will be 3140 m3/d in winter and 2700 m3/d in summer, other conditions unchanged. the pumping and injection rate are the same and constant

(2) Permeability coefficient

The permeability coefficient in the intermediate aquifer around sealed zone controls the flow velocity and direction of the recharge water to the pumping zone, which controls the thermal and flow breakthrough strength during the system operation. According to the corresponding strata of the sealed zone and the injection zone, the operation strategies of initial, increasing and decreasing permeability coefficient are designed respectively (Table 3).

Table 3 The operation plan of different hydraulic conductivity

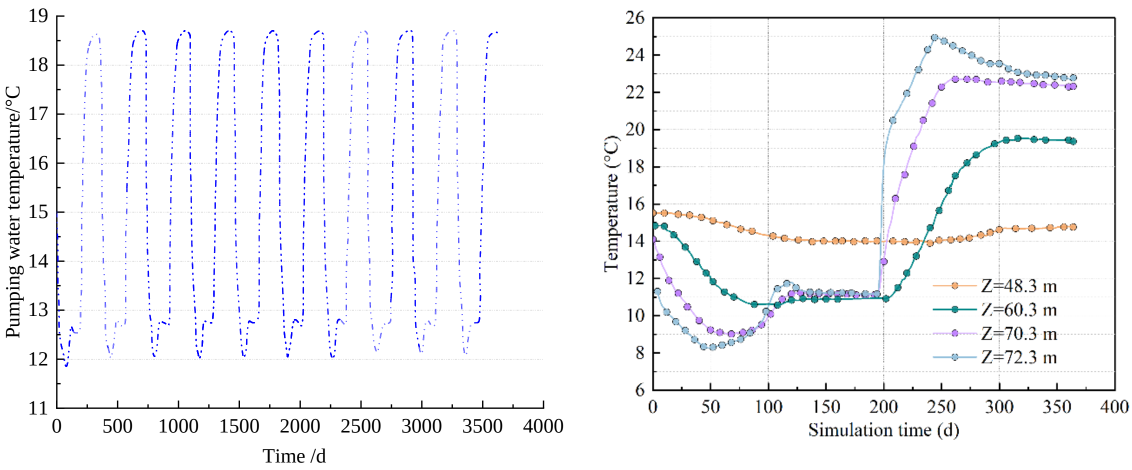
Zone	Initial		Increase		Decrease	
	$K_{xx}=K_{yy}$	K_z	$K_{xx}=K_{yy}$	K_z	$K_{xx}=K_{yy}$	K_z
II	1.35	1.35	2.70	2.70	1.35	2.70
III	5.8×10^{-3}	0.30	5.00	5.00	5.8×10^{-3}	5.8×10^{-3}
IV	1.8×10^{-4}	1.8×10^{-4}	5.00	5.00	1.8×10^{-4}	1.8×10^{-4}

5 RESULTS AND ANALYSIS

5.1 Evolution trend of temperature field

Fig. 8a shows the temperature dynamic change curve of the single-well circulating geothermal energy extracted system operating for 10 years under both winter heating and summer cooling conditions. The outlet water temperature shows a significant periodic dynamic change law with the operation. The outlet water temperature decreases in the heating period and slowly recovers after the natural heat exchange with the stratum. In the cooling period, the outlet water temperature begins to rise as the high temperature injection water is continuously injected. At the end of the first cooling season, the outlet water temperature increased by 3.13 ℃ over the initial aquifer temperature, and thereafter the 10th heating period, the outlet water temperature was 12.05 ℃, which is 0.25 ℃ higher than that of the first heating period late stage. The aquifer has the advantage of natural energy storage, storing cold in winter and heat in summer. The two-stage complementarity eliminates the energy loss in system operation. Although the pumping temperature cannot be restored to the initial level, it keeps the overall stability and ensures the operation efficiency of the single-well circulating geothermal energy collection system.

Fig. 8 (b) shows the temperature variation characteristic curve at different depths of the vertical profile of aquifer, where Z=72.3m and Z=70.3m refer to the upper interface and lower interface of the sealed zone, respectively (Z represents the distance to the aquifer floor). At the early stage of operation, forced convective heat transfer occurs between the cold water and the aquifer skeleton, and the aquifer temperature at the bottom of the injection zone first drops rapidly, and part of the injection water flows into the pumping zone. Flow breakthrough is accompanied by heat breakthrough, and the pumping zone near the sealed section is more susceptible to injection-water due to insufficient heat transfer, showing that the temperature change of the aquifer at Z=60.3m is more rapid and drastic than that at Z=48.3m. The trend of temperature variation at different depths during the cooling period in summer is the same as that in winter, but the trend of aquifer temperature decrease turns to temperature increase.

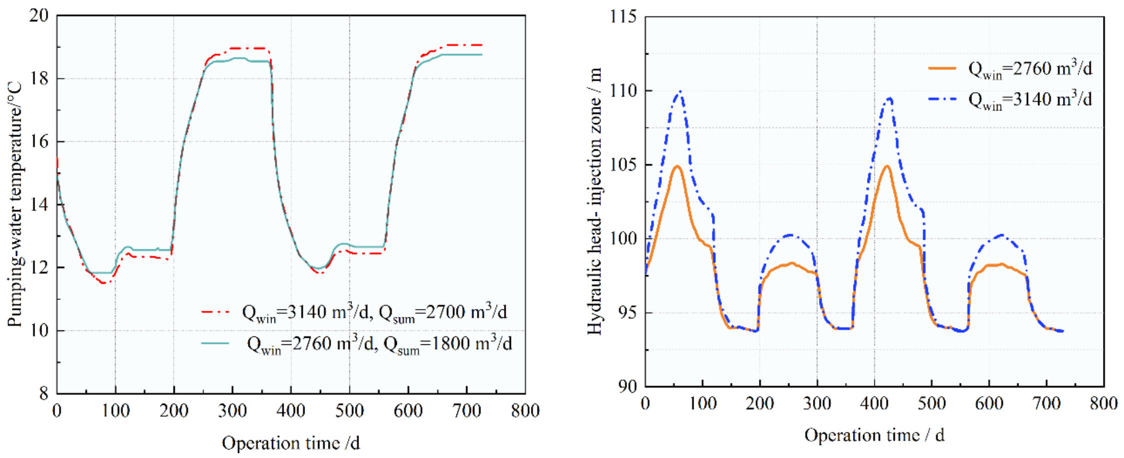


a) b)

Fig. 8 The dynamic evolution of the outlet temperature for a single well system a) 10 year's operation with heating and cooling; b) Temperature-time relation curve in different depth of aquifer

5.2 Influence of pumping flow rate

The variation of pumping water temperature and hydraulic head around injection zone with the operation of SWC under different pumping flow rates is shown in Fig. 9. As shown in the figure, the increase in flow rate has a more significant impact on the hydraulic head. The injection water entering the aquifer through the injection section well wall consumes kinetic energy, superimposed on the resistance of the porous medium, and the groundwater level around the water injection section is continuously raised to form a water mound centered on the injection well. The increase of pumping water means that the amount of injection water increases at the same time, the hydraulic head around the injection well is raised by 5 m compared with the low pumping flow rate after the first heating season. The hydraulic head rise of injection zone in the cooling season is lower than that in the heating period, considering the p the positive ratio of the liquid dynamic viscosity coefficient to the temperature. In winter, the injection water temperature is lower than that of aquifer, the dynamic viscosity coefficient of cold liquid is higher, which increases the flow resistance of groundwater energy in porous medium, and vice versa in summer. The variation of pumping temperature does not exceed 0.30 ℃, indicating that the increase of pumping flow rate has little influence on temperature, but the heat production of the system increases by 45%, which is beneficial to improve the operation efficiency.

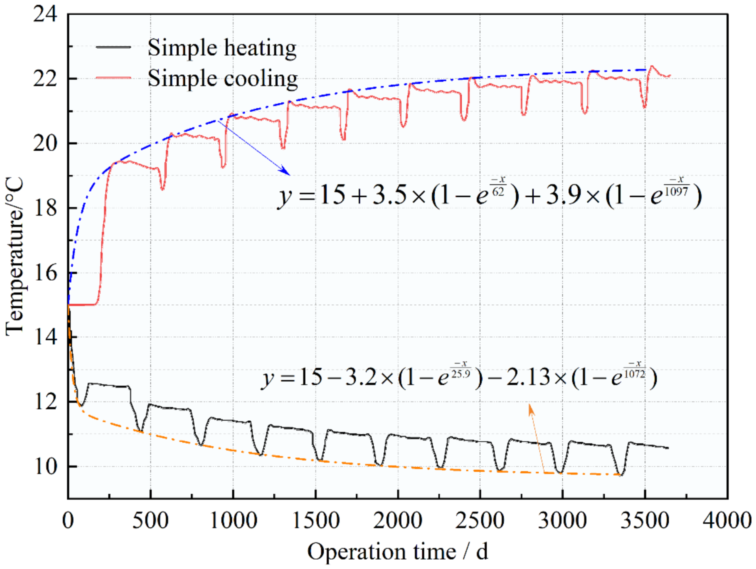


a) b)

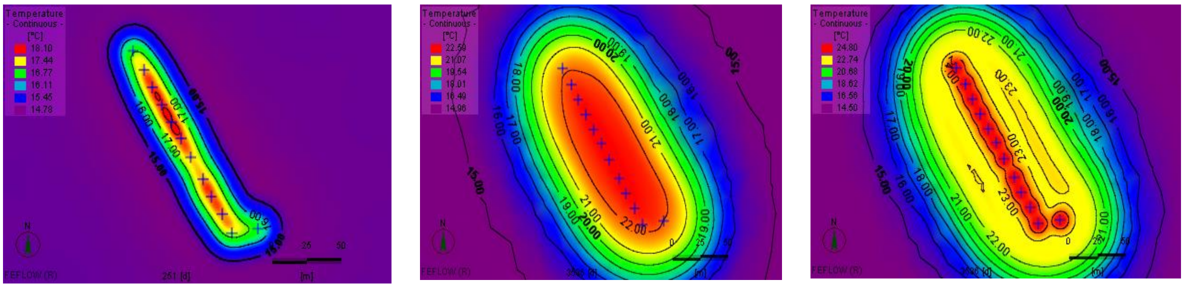
Fig. 9 The evolution of the a) Pumping water temperature; b) Hydraulic head around injection zone with different pumping flow

5.3 Influence of single-season operation mode

The influence of single-season operation mode on pumping temperature of SWC refers to Fig. 10. It can be seen the pumping temperature constantly presents a dynamic change process of "reduction-recovery" under the long-term operation of simple heating mode. After 7 years of continuous operation, the pumping temperature reached a stable state and maintained around 22 ℃. After the 10th heating season, the pumping temperature decreased by 5.28 ℃ compared with the initial aquifer temperature. In the simple cooling mode, the overall pumping temperature showed an upward trend, and the pumping temperature increased by 7.31 ℃ after the 10th cooling season. It can be seen from the aquifer temperature graph (Fig. 10b) that the thermal breakthrough occurred in the pumping zone when the first cooling period finished. With the increase of the operating life, the strength of thermal breakthrough intensified and the thermal response radius of the SWC system extended and expanded. In addition, the temperature change of the aquifer corresponding to the injection zone is most affected by the recharge water, and the radius of thermal plume is wider than that of the pumping section. After the operation, the temperature of the backwater section near the heat source well reaches 24.8 ℃, which is 1.5 ℃ higher than that of the pumping zone.



a)



Pumping zone (1st cooling period) Pumping zone (10th cooling period) Injection zone (10th cooling period)

b)

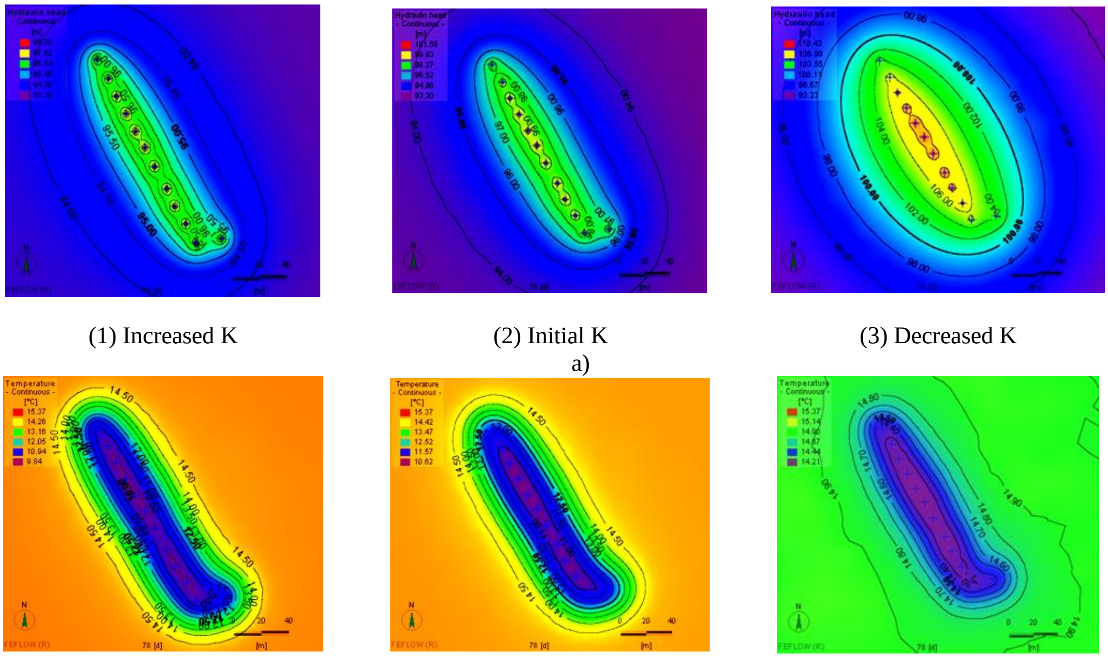
Fig. 10 Single season operation model influenced on temperature variation: a) Outlet temperature; b) Aquifer temperature

The pumping temperature of the SWC system gradually increases (summer) or decreases (winter) with the simple cooling or heating, respectively. With the decrease of heat exchange temperature difference, the energy efficiency of the system is reduced, which is not enough to bear the energy demand of the user side, and the phenomenon of energy absorption attenuation will occur in long-term single-season operation. Compared with Fig. 8a, the recovery of pumping temperature under annual operation is more significant than that of simple cooling or heating.

5.4 Influence of permeability

Fig. 11 shows the influence of permeability coefficients (K) of aquifer in the middle of pumping and injection section on seepage field and temperature field. The middle aquifer plays an aquitard when its permeability coefficient is reduced, and the main seepage direction of the injection water enters the aquifer is changed to the horizontal direction, which is manifested by the diffusion extension of the recharge water margin. The influence radius of the groundwater mound is far away from the thermal well, the hydraulic head center of the water mound reaches 107.42 m, which is higher than super permeability coefficient is obtained.

The temperature distribution of aquifer in pumping zone is greatly affected by the permeability of middle aquifer. When the K is decreased, hydraulic connects between injection and pumping zone is weakened, which lead to the proportion of the recharge water vertical flowing into the pumping zone reduced, delaying the occurrence and strength of thermal breakthrough. Correspondingly, the aquifer temperature around pumping zone is less effected by the injection water, and the temperature near the thermal well is 1.3 ℃ lower than initial aquifer, which is less than the temperature drop of 5.66 ℃ while the K increase. The same trend exists in the thermal radius.



(1) Increased K (2) Initial K (3) Decreased K

a)

(4) Increased K (5) Initial K (6) Decreased K

b)

Fig. 11 Influence of the different hydraulic conductivity on a) Seepage filed of injection zone; b) Temperature field of pumping zone

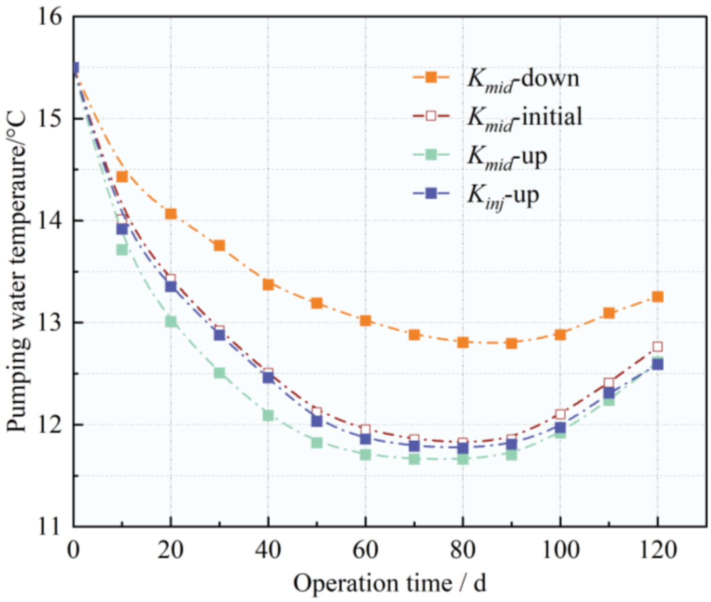


Fig. 12 Pumping water temperature evolution with different hydraulic conductivity

Figure 12 indicates that when the K of the middle aquifer decreases, the pumping temperature reduction is small, which can effectively maintain the temperature difference between the inlet and outlet of heat exchanger, as well as improve the heat exchange efficiency of the SWC system. The influence of the K of the aquifer around pumping zone is more obvious than that of pumping temperature. When planning the geothermal extraction system under similar hydrogeological conditions, the sealed zone should be set in the aquifer with small permeability coefficient as far as possible.

6 CONSLUSION

In this paper, the operation principle and applicable characteristics of three different modes of single-well circulating geothermal collection system are indicated. According to the SWC system without the backfilled particles, the mathematical model of groundwater seepage in confined aquifer is established, and the motion equation of a single water collection building with both pumping function and injecting function is derived by superposition principle. Finally, the temporal and spatial evolution of seepage field and temperature field of SWC system with different pumping flow rate, operation modes and aquifer permeability coefficient are analyzed by numerical simulation. The main conclusions are as follows:

(1) When the pumping flow increases by 50%, the waterhead at the injection section increases by 5m, while the pumping temperature changes by only 0.3 ºC. affected by the dynamic viscosity coefficient of the injection water, the height of the water mound centers on injection zone in cooling period is lower than that in heating season.

(2) Simple cooling or heating mode is unfavorable to the system operation, the overall evolution trend of outlet water temperature shows an upward (simple cooling) or downward (simple heating), and the energy production attenuation occurs. Under the long-term operation of an annual mode (cooling & heating), the pumping temperature is stable to ensure the system sustainability.

(3) The permeability coefficient of intermediate aquifer has more significant influence on the seepage field and temperature field of aquifer. When the K of the intermediate aquifer is reduced, the hydraulic head around injection zone is significantly elevated, which reduces the recharge water flowing to the pumping zone and delays the occurrence time and intensity of thermal breakthrough.

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